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AUTONOMOUS CONTROL PROCEDURES FOR SHUTTLE RENDEZVOUS PROXIMITY OPERATIONS

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ABSTRACT

This paper presents the results of a study which uses fuzzy sets to model a Space Shuttle pilot's reasoning and actions while performing rendezvous proximity operation maneuvers. Use of conventional pilot models is limited since they often results in unrealistic overfirings and, therefore, excess fuel usage and unacceptable playload contamination and plume disturbances. In this model fuzzy sets are used to simulate smooth and continuous actions as would be expected from an experienced pilot and to simulate common sense reasoning in the decision process. The present model assumes visual information available to the Shuttle pilot from the Shuttle Crew Optical Alignment Sighting (COAS) device and the overhead window and rendezvous radar sensor information available to him from an onboard display.

This model will be used in a flight analysis simulator to perform studies requiring a large number of runs, each of which currently needs an engineer in the loop to supply the piloting decisions. A great deal of the engineer's time is required for this repetitious and somewhat boring function. This work has much broader implications in control of robots such as the Flight Telerobotic Servicer, in automated pilot control and attitude control, and in advisory and evaluation functions that could be used for flight data monitoring or for testing of various rule sets in flight preparation.

INTRODUCTION

The manual phase of Space Shuttle rendezvous begins several nautical miles from the target when the crew starts maneuvering the Shuttle using visual and sensory information. This portion of rendezvous is referred to as terminal phase.

Once terminal phase begins the crew can fly a number of scenarios, or paths, to approach the target. One sequence is illustrated in figure 1. The coordinate system is centered at the target, and has a v-bar axis tangential to the target's orbit and positive in its direction of motion. The r-bar axis is perpendicular to the v-bar axis with the positive direction towards the center of the earth. The Shuttle flies to the v-bar axis several hundred feet in front of the target. There the upward velocity is nulled to zero, and the vehicle begins "closing" toward the target by decreasing its velocity relative to the target's velocity so that the two will eventually rendezvous.

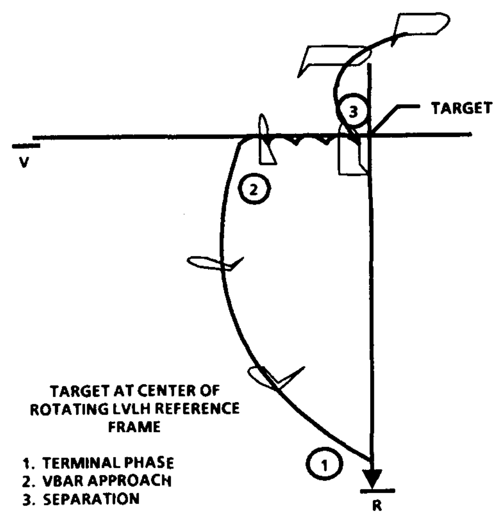

figure 1

One simulation available for these so called "proximity operations" is the Shuttle Engineering Simulator (SES), a high fidelity simulation complete with cockpit. It is expensive to operate, heavily scheduled and

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must frequently be reserved for crew training. For certain engineering studies that do not require SES fidelity, a "desk top" simulator [1, 2] implemented on an HP 9000 is adequate. A "pilot" controls the "vehicle" by input through a keyboard or, sometimes, a joystick. Decisions to "fire jets" are made based on CRT graphical representations of the view through the Shuttle overhead window, the scenes from closed circuit television cameras mounted in the payload bay and the view through the Crew Optical Alinement Sight (COAS). Digital data on the CRT represents information provided the Shuttle crew through onboard CRT displays. Included in this data are rendezvous radar measurements of range and range rate, which are updated at the simulation integration rate.

There are several motives for wanting to program an automatic pilot that can "fly" this simulation. An automatic pilot that realistically represented human response could make it possible to obtain many executions in a batch mode that presently require an engineer in the loop. If a number of executions are needed to obtain statistics on various parameters, such as fuel usage, contamination, or plume impingement, a great deal of engineering time can be required. Run time could be reduced since creation of the graphic output at a realtime response rate could be eliminated. Further, once an engineer playing pilot has performed ten or so simulations of a proximity operations scenario, the effort of learning for that scenario is unrealistically high, which causes the results to be overly optimistic.

Existing automatic pilots for a batch-mode simulation were found to be almost as labor intensive as having an engineer in the loop. A given scenario might need to be executed repeatedly and "tuned" to determine when and what thrusters should fire before the desired results can be obtained. This effort was necessary to avoid the overfirings that frequently resulted in excess fuel usage and unacceptable payload contamination and plume disturbances due to the "crispness" of the commands in the logic coded to do the piloting.

The need then is to create decision making logic that results in the same common sense decisions a pilot would make. Since the pilot uses his experience combined with the imprecise visual and digital information available to him, it appeared that fuzzy logic would provided a good basis for simulating his decision making.

Furthermore, it was realized that this approach could be adapted to a number of areas of interest, such as development of translational and rotational digital autopilots, telerobotics, remote vehicle control, as well as ground or onboard advisory and evaluation functions.

A low level study effort has been underway for several months. The results and status to date are presented below.

DESIGN AND IMPLEMENTATION

Design and implementation of the pilot proceeded as follows. A set of rules of the kind observed and followed by Shuttle pilots flying a proximity operations scenario of the type illustrated in figure 1 was developed by observing and communicating with pilots of simulators used in Shuttle training and evaluation and testing at the Johnson Space Center. These rules were stated in natural language as they were related to us by the various pilots. The rules deal with the Shuttle keeping both the desired vertical distance and the desired closing velocity with respect to the target. The visuals that were used in this study were restricted to the COAS and the overhead window, which are illustrated in figure 2, and the digital data display of range and range rate from the rendezvous radar.

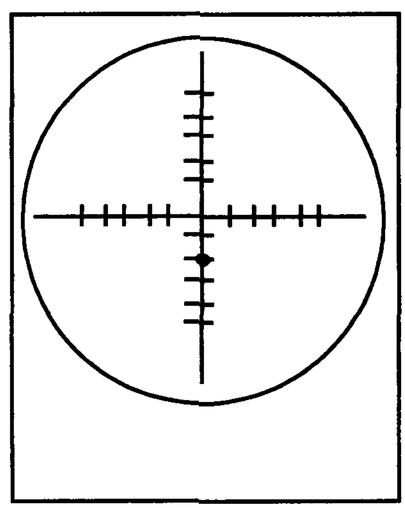

figure 2

Typical rules maintaining the desired vertical relationship are of the following form:

> If the target is located near the center of the field of view of the COAS , then no action is needed to raise or lower the shuttle.
>
> If the target is significantly above or below the center of the field of view of the COAS, then jets must be fired to lower or raise the shuttle.

The following rule is used to maintain the desired horizonal closing relationship:

> If the Shuttle is at a braking gate, e.g., 1000 ft, 500 ft, 400 ft, ..., from the target, then the closing velocity should be 1.0 fps, .5 fps, .4fps, ...

To implement these rules using fuzzy sets it was necessary to examine more closely what was meant by phrases such as "near" the center and "significantly" above or below. These terms are definitely descriptors of sets with fuzzy boundaries.

It was decided to use the π and S functions as given in [3, 4] since they can easily be adjusted for different degrees of "fuzziness" by varying the parameters that define their width and shape. The equations of the π and S functions are given below.

$$
\begin{aligned}
S(x,a,b,c) &= 0 && \text{for } x \leqq a \\
&= 2((x - a)/(c - a))^{**}2 && \text{for } a \leqq x \leqq b \\
&= 1 - 2((x - c)/(c - a))^{**}2 && \text{for } b \leqq x \leqq c \\
&= 1 && \text{for } x \geqq c
\end{aligned}
$$

$$
\begin{aligned}
\pi(x,b,c) &= S(x, c - b, c - b/2, c) && \text{for } x \leqq c \\
&= 1 - S(x, c, c + b/2, c + b) && \text{for } x \geqq c
\end{aligned}
$$

Graphs of the general S and π functions are given in figure 3.

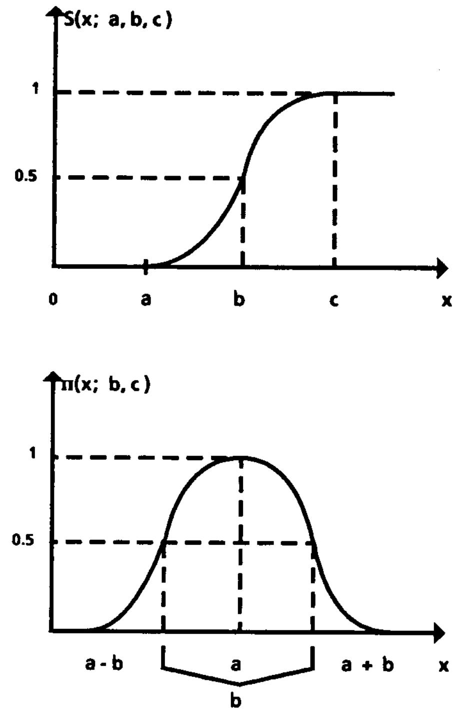

figure 3

As can be seen, one can effect a rapid or slow transisition from complete membership to complete non-membership by altering the parameters a, b, and c or b and c for the S or π function respectively. For example, the graphs of the S and π functions used for the maintainance of vertical position are given in figure 4. These functions allow flexibility in simulating different style pilots, for example, those who attempt to keep the target very close to the center of the field of view at all times, those who are more relaxed and are concerned mostly with keeping the target in view and using orbital mechanic effects to their advantage, and any type of pilot between these extremes.

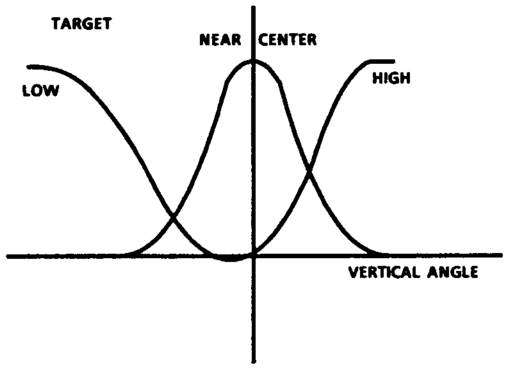

figure 4

The functions are used as follows. Fuzzy sets were defined for "somewhat greater than", "somewhat less than", and "approximately equal to" the desired closing rate. They were also defined for "high", "low", and "near the center" in the field of view. Approximately every twenty seconds, a time interval considered sufficient for a pilot to deal with the visual and displayed noisy range and range rate information, the fuzzy sets were evaluated and the maximum value recorded for each set of three functions corresponding respectively to closing rate and location in the field of view. Indices identifying the fuzzy function with the larger value for each set were recorded. If both indices corresponds to the no change fuzzy functions then no action is taken, if exactly one indicates no change then the action corresponding to the other maximum value is taken, and if both indicate action should be taken then the action corresponding to the larger of the two is taken.

The action to be taken, which is a certain number of jet firings, is determined as follows. The velocity change required to effect a vertical position change or to increase or decrease the closing rate is divided by the proper setting of the digital autopilot (DAP). The DAP has two settings that are preloaded with values that control the magnitude of the jet firings. Typical values are 0.02 and 0.05 which translates into 0.02 or 0.05 feet per second change in velocity per pulse depending on which value has been selected. The nominal DAP setting is the larger of the two and is the proper setting if it is smaller than the required velocity change. If this setting exceeds the required velocity change then the proper setting is the smaller value. The selected number, which could be considered the appropriate number of pulses under ideal conditions, is then weighted by multiplying by the fuzzy set evaluation that has been saved. This is the number of pulses that is commanded to the jets in the required direction.

To illustrate the number of pulses computation consider figure 5.

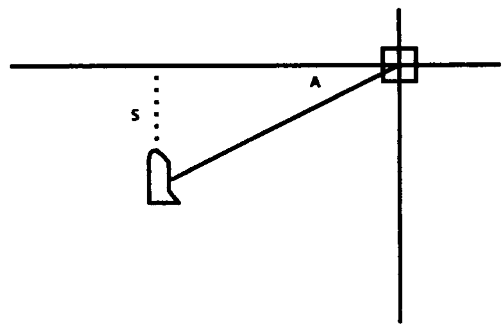

figure 5

In this case the target is high in the field of view. By using the shuttle-target range the angle A can be used to compute s, the distance below the target. Using the equation $\Delta h = .56\ \Delta v$, which relates Δh in nautical miles to Δv in feet per second one can estimate the required Δv to move the shuttle up to the v-bar. This estimate of Δv is adjusted according to whether the shuttle is currently moving up or down relative the target. This Δv can then be converted into an "ideal" number of pulses by dividing by the DAP setting, d. If f(A) is the evaluation of the fuzzy function corresponding to target high in the field of view then the number of pulses to be applied is given by

$$N = (\Delta v/d)^* f(A)$$

Closing rate control is easier in theory since one only has to difference actual closing rate and desired closing rate and divide by the DAP setting. In practice however it is considerably harder since range rate obtained from the radar is corrupted by noise and bias which at close ranges can be on the order of magnitude of the closing rates that need to be maintained. This problem, which is essentially one of modeling a human method of visually monitoring a stream of data and extracting the center of the data, is currently being considered. Some initial efforts look promising but have not been tested sufficiently at this time.

RESULTS

The automatic pilot can presently perform a terminal phase approach to the v-bar and a closing approach along the v-bar and maintain the desired line of sight and closing rates in a manner that compares reasonably well to the response of a "nominal" pilot. A "nominal" pilot is considered one that performs maneuvers in a manner recognized as appropriate in flight planning material. "Nominal" means the pilot does not allow the Shuttle's position and velocity to deviate greatly from the planned scenario.

The following table shows propellant consumption data tabulated from flying five dispersed proximity operation profiles of the type illustrated in figure 1. Both manually controlled and automated pilot controlled are given and it can be seen that the automated pilot controller compares favorably to the manually flown profile. It is at least within ten percent for each case. Dispersed means that the beginning states are randomly selected and that the noise and bias in the rendezvous radar are randomly varied within radar specification limitations.

ORBITER RCS PROPELLANT CONSUMPTION

MIL - MAN - IN - A - LOOP

ORBITER V-BAR APPROACH FROM 500 TO 60 FT FLIGHT PROFILE SCENARIOS	** PROPELLANT CONSUMPTION TOTAL (LBS)
(MIL) APPROACH DESPERSED CASE 1	101.0
(MIL) APPROACH DESPERSED CASE 2	107.0
(MIL) APPROACH DESPERSED CASE 3	126.0
(MIL) APPROACH DESPERSED CASE 4	119.0
(MIL) APPROACH DESPERSED CASE 5	116.0
AUTO - PILOT APPROACH DESPERSED CASE 1	110.0
AUTO - PILOT APPROACH DESPERSED CASE 2	115.0
AUTO - PILOT APPROACH DESPERSED CASE 3	120.0
AUTO - PILOT APPROACH DESPERSED CASE 4	127.0
AUTO - PILOT APPROACH DESPERSED CASE 5	122.0

** PROPELLANT NUMBERS ARE NOT A STATISTICAL MEAN BUT ARE REPRESENTATIVE OF THE NUMBER OF FLIGHT PROFILES FLOWN

Figure 6 illustrates a typical man-in-the-loop trajectory as contrasted with a profile generated by the automated pilot. Note that the trajectories are similar for the two cases..

TYPICAL V-BAR APPROACH TRAJECTORY EXAMPLE

MAN - IN - THE - LOOP (MIL) VS. AUTOMATED PILOT

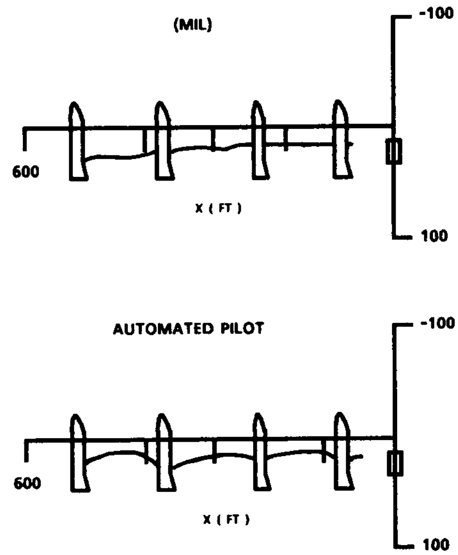

figure 6

STATUS AND CONCLUSIONS

The preliminary results of an automatic pilot for a low-fidelity Shuttle proximity operations simulator that maneuvers based on fuzzy decision functions indicate the goals of the study is achieveable. That is, it appears to be possible to simulate the common sense reasoning of a pilot using fuzzy decision functions to express rules obtained from experienced pilots.

A great deal of work must be completed to recognize the full potential of the concept, however. First, we realize improvements can be nade to the existing rules. These improvements will give more versatility to the reasoning and will incorporate additional fuzzy decision functions. An example is to give more emphasis to the vertical rate of the Shuttle to decide if the Shuttle needs to be raised or lowered. The present version does not deal with out-of-plane errors. In addition there are many more scenarios to address.

For expediency, the automatic pilot was implemented in Fortran, but it is apparent that a rule based expert system shell would provide a better implementation language and a conversion will be made as soon as possible.

While the parameters chosen for the curves used in the fuzzy functions result in appropriate decisions for a wide range of input for a given scenario, it may be desireable to allow the user to determine the piloting characteristics he would like simulated, and have the software select the parameters based on this description. For example, does the pilot respond quickly to deviations from the desired path, or does he allow errors larger than considered "average" to accumulate before he reacts. Results indicate a method could be devised to accomplish this.

As the approach is extended to other applications, or possibly to speed up use of the present application, it is realized that a fuzzy function chip could be used to offload a great deal of the computation. This would be especially appropriate to study the application of the concept to realtime rotational and translational digital autopilots.

ACKNOWLEDGEMENTS

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